

CLAIMS

1. A method of simulating, in a machine, a string using a wave equation that relates movement of the string in time to force acting on the string,
wherein the force acting on the string simulates a stream of a fluid medium flowing relative to the string.
2. A method according to claim 1, wherein:
the simulated string is supported between two supports and is aligned at rest in a first direction between the two supports;
a first of the two supports allows movement in a second direction orthogonal to the first direction and a second of the two supports does not allow movement; and
the string is caused from rest to vibrate in a plane, which includes the first and second directions, by turbulence in the fluid flow causing the stream of fluid medium to exert a pressure on the string in the second direction.
3. A method according to claim 2, wherein:
movement of the string out of alignment with the first direction causes the stream of fluid medium flowing in the first direction to exert a force on the string in the second direction.
4. A method according to claim 1, wherein:
the simulated string is supported between two supports aligned in a first direction,
a first of the two supports is rigid and a second of the two supports allows movement in a second direction orthogonal to the first direction; and
the string is caused to vibrate in a plane, which includes the first and second directions, by the stream of fluid medium flowing in a direction having a component in the second direction.
5. A method according to claim 1, wherein:
the simulated string is supported between two supports aligned in an x-direction;
a first of the two supports allows movement in a y-direction orthogonal to the x-direction and a second of the two supports does not allow movement;

the string comprises a plurality of discrete elements aligned at rest in the x-direction and spaced apart by a distance dx ; and

the discrete elements are able to move in discrete steps of time dt in the y-direction only.

6. A method according to claim 5, in which the string comprises a plurality of j discrete elements from $j=0$ at one end movably supported by the first support to $j=x-1$ at the opposite end immovably supported by the second support; wherein

j is an integer; and

the stream of fluid medium flows in the x-direction and exerts a pressure on the string between elements $j=0$ and $j=1$.

7. A method according to claim 6, wherein the force $F_{PRES}[n, 0]$ at time n acting on the immovably supported element $j=0$ due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$ is given by:

$$F_{PRES}[n, 0] = P * (y[n, 0] - y[n, 1]) / dx$$

in which:

P denotes the pressure exerted by the stream of fluid medium on the string between the movably supported element $j=0$ and adjacent element $j=1$;

$y[n, 0]$ denotes the excursion of the movably supported element $j=0$ at time n ; and

$y[n, 1]$ denotes the excursion of the adjacent element $j=1$ at time n .

8. A method according to claim 6, wherein the force $F_{TURB}[n, 0]$ at time n acting on the immovably supported element $j=0$ due to the turbulence in the stream of fluid medium is given by:

$$F_{TURB}[n, 0] = C_{TURB} * N_{RND}[n]$$

in which:

C_{TURB} denotes a turbulence coefficient; and

$N_{RND}[n]$ denotes a random signal.

9. A method according to claim 8, wherein the random signal comprises a low pass filtered noise.

10. A method according to claim 6, wherein the excursion $y[n+1, 0]$ of the movably supported element for the next sample due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$ is given by:

$$y[n+1, 0] = y[n, 0] + (F_{\text{PRES}}[n, 0] + F_{\text{TURB}}[n, 0]) * dt^2 / M[0]$$

in which:

$y[n, 0]$ denotes the excursion of the movably supported element $j=0$ at time n ; and

$F_{\text{PRES}}[n, 0]$ denotes the force at time n acting on the movably supported element $j=0$ due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$;

$F_{\text{TURB}}[n, 0]$ denotes the force at time n acting on the movably supported element $j=0$ due to the turbulence in the stream of fluid medium; and

$M[0]$ denotes the mass of the movably supported element $j=0$.

11. A method according to claim 10, wherein the excursion $y[n+1, 0]$ is limited.

12. A method according to claim 6, wherein the stream of the fluid medium exerts a pressure on the string between each of the elements; and

wherein the force $F[n, j]$ at time n acting on each discrete element from $j=1$ to $j=x-2$ due to the pressure P is given by:

$$F[n, j] = P[j] * (y[n, j] - y[n, j-1]) / dx + P[j] * (y[n, j] - y[n, j+1]) / dx.$$

13. A method according to claim 12, wherein the pressure P decreases linearly or exponentially with increasing j

14. A method according to claim 5, wherein the wave equation is an approximation of the continuous wave equation

$$M \frac{\partial^2 y}{\partial t^2} = T \frac{\partial^2 y}{\partial x^2} - S \frac{\partial^4 y}{\partial x^4} + L_T \frac{\partial^3 y}{\partial x^2 \partial t} - L_S \frac{\partial^5 y}{\partial x^4 \partial t} - L_V \frac{\partial y}{\partial t} + F(x, t)$$

in which:

$F(x, t)$ denotes an external force at coordinate x on the string at time t ;

M denotes mass per length;

S denotes stiffness of the string;

T denotes tension of the string;

L_S denotes a loss associated with the stiffness of the string;

L_T denotes a loss associated with the tension of the string; and

L_V denotes a loss associated with the turbulent flow of the fluid medium.

15. A method according to claim 14, wherein the approximation of the continuous wave equation is the discrete recursion formula:

$$y[n+1, j] = (y[n, j-2] c_1 + y[n, j-1] c_2 + y[n, j] c_3 + y[n, j+1] c_2 + y[n, j+2] c_1 + y[n-1, j-2] c_4 + y[n-1, j-1] c_5 + y[n-1, j] c_6 + y[n-1, j+1] c_5 + y[n-1, j+2] c_4) / M[j] + 2y[n, j] + F[n, j]/M[j]$$

in which:

$$dx = 1;$$

$$dt = 1;$$

$y[n, j]$ denotes the excursion of discrete element j in the y -direction at time n ;

$y[n+1, j]$ denotes the excursion of discrete element j in the y -direction at time $n+1$;

$y[n, j+1]$ denotes the excursion of discrete element $j+1$ in the y -direction at time n ;

$M[j]$ denotes the mass of discrete element j ;

$F[n, j]$ denotes an additional external force acting on a discrete element j at time n ; and

c_1 to c_6 are coefficients, which depend on the material parameters of the string and the surrounding media.

16. A method according to claim 15, wherein

$$c_1 = -(S + L_S);$$

$$c_2 = T + 4S + L_T + 4L_S;$$

$$c_3 = -(2T + 6S + L_V + 2L_T + 6L_S);$$

$$c_4 = L_S;$$

$$c5 = -(Lt + 4Ls); \text{ and}$$

$$c6 = Lv + 2Lt + 6Ls$$

17. A method according to claim 15, wherein the discrete recursion formula is solved for the elements adjacent the respective supports by providing a dummy element at opposite ends of the string so that the excursion $y[n+1, -1]$ of a dummy element adjacent the movably supported element for the next sample is given by:

$$y[n+1, -1] = y[n+1, 0] - (y[n+1, 1] - y[n+1, 0])$$

and the excursion $y[n+1, x]$ of a dummy element adjacent the immovably supported element for the next sample is given by:

$$y[n+1, x] = -y[n+1, x-2]$$

18. A method according to claim 1, further comprising generating a sound based on movement of the simulated string.

19. A machine readable medium providing executable computer program instructions which when executed cause a data processing system to perform a method of simulating, in a machine, a string using a wave equation that relates movement of the string in time to force acting on the string,

wherein the force acting on the string simulates a stream of a fluid medium flowing relative to the string.

20. A method according to claim 19, wherein:

the simulated string is supported between two supports and is aligned at rest in a first direction between the two supports;

a first of the two supports allows movement in a second direction orthogonal to the first direction and a second of the two supports does not allow movement; and

the string is caused from rest to vibrate in a plane, which includes the first and second directions, by turbulence in the fluid flow causing the stream of fluid medium to exert a pressure on the string in the second direction.

21. A method according to claim 20, wherein:
 movement of the string out of alignment with the first direction causes the stream of fluid medium flowing in the first direction to exert a force on the string in the second direction.
22. A method according to claim 19, wherein:
 the simulated string is supported between two supports aligned in a first direction,
 a first of the two supports is rigid and a second of the two supports allows movement in a second direction orthogonal to the first direction; and
 the string is caused to vibrate in a plane, which includes the first and second directions, by the stream of fluid medium flowing in a direction having a component in the second direction.
23. A method according to claim 19, wherein:
 the simulated string is supported between two supports aligned in an x-direction;
 a first of the two supports allows movement in a y-direction orthogonal to the x-direction and a second of the two supports does not allow movement;
 the string comprises a plurality of discrete elements aligned at rest in the x-direction and spaced apart by a distance dx ; and
 the discrete elements are able to move in discrete steps of time dt in the y-direction only.
24. A method according to claim 23, in which the string comprises a plurality of j discrete elements from $j=0$ at one end movably supported by the first support to $j=x-1$ at the opposite end immovably supported by the second support; wherein
 j is an integer; and
 the stream of fluid medium flows in the x-direction and exerts a pressure on the string between elements $j=0$ and $j=1$.
25. A method according to claim 24, wherein the force $F_{PRES}[n, 0]$ at time n acting on the immovably supported element $j=0$ due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$ is given by:

$$F_{\text{PRES}}[n, 0] = P * (y[n, 0] - y[n, 1]) / dx$$

in which:

P denotes the pressure exerted by the stream of fluid medium on the string between the movably supported element $j=0$ and adjacent element $j=1$;

$y[n, 0]$ denotes the excursion of the movably supported element $j=0$ at time n ; and

$y[n, 1]$ denotes the excursion of the adjacent element $j=1$ at time n .

26. A method according to claim 24, wherein the force $F_{\text{TURB}}[n, 0]$ at time n acting on the immovably supported element $j=0$ due to the turbulence in the stream of fluid medium is given by:

$$F_{\text{TURB}}[n, 0] = C_{\text{TURB}} * N_{\text{RND}}[n]$$

in which:

C_{TURB} denotes a turbulence coefficient; and

$N_{\text{RND}}[n]$ denotes a random signal.

27. A method according to claim 24, wherein the excursion $y[n+1, 0]$ of the movably supported element for the next sample due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$ is given by:

$$y[n+1, 0] = y[n, 0] + (F_{\text{PRES}}[n, 0] + F_{\text{TURB}}[n, 0]) * dt^2 / M[0]$$

in which:

$y[n, 0]$ denotes the excursion of the movably supported element $j=0$ at time n ; and

$F_{\text{PRES}}[n, 0]$ denotes the force at time n acting on the movably supported element $j=0$ due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$;

$F_{\text{TURB}}[n, 0]$ denotes the force at time n acting on the movably supported element $j=0$ due to the turbulence in the stream of fluid medium; and

$M[0]$ denotes the mass of the movably supported element $j=0$.

28. A method according to claim 27, wherein the excursion $y[n+1, 0]$ is limited.

29. A method according to claim 24, wherein the stream of the fluid medium exerts a pressure on the string between each of the elements; and

wherein the force $F[n, j]$ at time n acting on each discrete element from $j=1$ to $j=x-2$ due to the pressure P is given by:

$$F[n, j] = P[j] * (y[n, j] - y[n, j-1]) / dx + P[j] * (y[n, j] - y[n, j+1]) / dx.$$

30. A method according to claim 29, wherein the pressure P decreases linearly or exponentially with increasing j

31. A method according to claim 23, wherein the wave equation is an approximation of the continuous wave equation

$$M \frac{\partial^2 y}{\partial t^2} = T \frac{\partial^2 y}{\partial x^2} - S \frac{\partial^4 y}{\partial x^4} + L_T \frac{\partial^3 y}{\partial x^2 \partial t} - L_S \frac{\partial^5 y}{\partial x^4 \partial t} - L_V \frac{\partial y}{\partial t} + F(x, t)$$

in which:

$F(x, t)$ denotes an external force at coordinate x on the string at time t ;

M denotes mass per length;

S denotes stiffness of the string;

T denotes tension of the string;

L_S denotes a loss associated with the stiffness of the string;

L_T denotes a loss associated with the tension of the string; and

L_V denotes a loss associated with the turbulent flow of the fluid medium.

32. A method according to claim 31, wherein the approximation of the continuous wave equation is the discrete recursion formula:

$$\begin{aligned} y[n+1, j] = & (y[n, j-2] \ c1 + y[n, j-1] \ c2 + y[n, j] \ c3 + y[n, j+1] \ c2 + \\ & y[n, j+2] \ c1 + y[n-1, j-2] \ c4 + y[n-1, j-1] \ c5 + y[n-1, j] \ c6 + y[n-1, j+1] \ c5 + \\ & y[n-1, j+2] \ c4) / M[j] + 2y[n, j] + F[n, j]/M[j] \end{aligned}$$

in which:

$$dx = 1;$$

$dt = 1$;

$y[n, j]$ denotes the excursion of discrete element j in the y -direction at time n ;

$y[n+1, j]$ denotes the excursion of discrete element j in the y -direction at time $n+1$;

$y[n, j+1]$ denotes the excursion of discrete element $j+1$ in the y -direction at time n ;

$M[j]$ denotes the mass of discrete element j ;

$F[n, j]$ denotes an additional external force acting on a discrete element j at time n ; and

$c1$ to $c6$ are coefficients, which depend on the material parameters of the string and the surrounding media.

33. A method according to claim 32, wherein

$c1 = -(S + Ls)$;

$c2 = T + 4S + Lt + 4Ls$;

$c3 = -(2T + 6S + Lv + 2Lt + 6Ls)$;

$c4 = Ls$;

$c5 = -(Lt + 4Ls)$; and

$c6 = Lv + 2Lt + 6Ls$

34. A method according to claim 32, wherein the discrete recursion formula is solved for the elements adjacent the respective supports by providing a dummy element at opposite ends of the string so that the excursion $y[n+1, -1]$ of a dummy element adjacent the movably supported element for the next sample is given by:

$$y[n+1, -1] = y[n+1, 0] - (y[n+1, 1] - y[n+1, 0])$$

and the excursion $y[n+1, x]$ of a dummy element adjacent the immovably supported element for the next sample is given by:

$$y[n+1, x] = -y[n+1, x-2]$$

35. A method according to claim 19, the method further comprising generating a sound based on movement of the simulated string.

36. An apparatus for simulating, in a machine, a string using a wave equation that relates movement of the string in time to force acting on the string,

wherein the force acting on the string simulates a stream of a fluid medium flowing relative to the string, said apparatus comprising:

means for storing data for said simulating; and

means for simulating.

37. An apparatus according to claim 36, wherein:

the simulated string is supported between two supports and is aligned at rest in a first direction between the two supports;

a first of the two supports allows movement in a second direction orthogonal to the first direction and a second of the two supports does not allow movement; and

the string is caused from rest to vibrate in a plane, which includes the first and second directions, by turbulence in the fluid flow causing the stream of fluid medium to exert a pressure on the string in the second direction.

38. An apparatus according to claim 37, wherein:

movement of the string out of alignment with the first direction causes the stream of fluid medium flowing in the first direction to exert a force on the string in the second direction.

39. An apparatus according to claim 36, wherein:

the simulated string is supported between two supports aligned in a first direction,

a first of the two supports is rigid and a second of the two supports allows movement in a second direction orthogonal to the first direction; and

the string is caused to vibrate in a plane, which includes the first and second directions, by the stream of fluid medium flowing in a direction having a component in the second direction.

40. An apparatus according to claim 36, wherein:

the simulated string is supported between two supports aligned in an x-direction;

a first of the two supports allows movement in a y-direction orthogonal to the x-direction and a second of the two supports does not allow movement;

the string comprises a plurality of discrete elements aligned at rest in the x-direction and spaced apart by a distance dx ; and

the discrete elements are able to move in discrete steps of time dt in the y-direction only.

41. An apparatus according to claim 40, in which the string comprises a plurality of j discrete elements from $j=0$ at one end movably supported by the first support to $j=x-1$ at the opposite end immovably supported by the second support; wherein

j is an integer; and

the stream of fluid medium flows in the x-direction and exerts a pressure on the string between elements $j=0$ and $j=1$.

42. An apparatus according to claim 41, wherein the force $F_{PRES}[n, 0]$ at time n acting on the immovably supported element $j=0$ due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$ is given by:

$$F_{PRES}[n, 0] = P * (y[n, 0] - y[n, 1]) / dx$$

in which:

P denotes the pressure exerted by the stream of fluid medium on the string between the movably supported element $j=0$ and adjacent element $j=1$;

$y[n, 0]$ denotes the excursion of the movably supported element $j=0$ at time n ; and

$y[n, 1]$ denotes the excursion of the adjacent element $j=1$ at time n .

43. An apparatus according to claim 41, wherein the force $F_{TURB}[n, 0]$ at time n acting on the immovably supported element $j=0$ due to the turbulence in the stream of fluid medium is given by:

$$F_{TURB}[n, 0] = C_{TURB} * N_{RND}[n]$$

in which:

C_{TURB} denotes a turbulence coefficient; and

$N_{RND}[n]$ denotes a random signal.

44. An apparatus according to claim 36, further comprising a means for generating sound based on said simulating.

45. An apparatus according to claim 41, wherein the excursion $y[n+1, 0]$ of the movably supported element for the next sample due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$ is given by:

$$y[n+1, 0] = y[n, 0] + (F_{\text{PRES}}[n, 0] + F_{\text{TURB}}[n, 0]) * dt^2 / M[0]$$

in which:

$y[n, 0]$ denotes the excursion of the movably supported element $j=0$ at time n ; and

$F_{\text{PRES}}[n, 0]$ denotes the force at time n acting on the movably supported element $j=0$ due to the pressure on the string between the movably supported element $j=0$ and adjacent element $j=1$;

$F_{\text{TURB}}[n, 0]$ denotes the force at time n acting on the movably supported element $j=0$ due to the turbulence in the stream of fluid medium; and

$M[0]$ denotes the mass of the movably supported element $j=0$.